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A DEA approach for estimating the agricultural energy and environmental efficiency of EU countries

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ABSTRACT

This study attempts to evaluate the energy and environmental efficiency of the primary sectors of the EU member state countries. The evaluation is based on a non-radial Data Envelopment Analysis (DEA) model which allows for non-proportional adjustments to energy inputs and undesirable outputs and thus it provides different estimations for energy and environmental efficiency scores. The 2001–2008 time period was selected for this research. One of the most important findings is that countries like Germany, Sweden, or Austria, with strong environmental protection standards, appear to be less energy and environmentally efficient, compared with countries like Denmark, Belgium, Spain, France, or Ireland. In addition, a series of eastern European countries achieve low efficiency scores, which can be characterized as expectable, due to low technology level being implemented in the primary production process. There are also two sub-periods for this research. The first one (2001–2006) covers the fully coupled with specific cultivations period for subsidy administation, and the second (2007–2008) where the new decoupled subsidy scheme was implemented. There are significant hints for considerable changes of energy and environmental efficiency after the implementation of the the new CAP, with the new member states siginificantly differ of both energy and environmental efficiency copmared with the older ones.

Contents

1. Introduction

One of the major objectives of the EU economic policy and development strategy is to become a low-carbon and resource-efficient economy. According to this goal by the year 2020 EU needs to increase the efficiency of energy use by 20%, decrease the CO_2 emissions by 20% and produce the 20% of the overall energy being consumed by renewable energy resources (20–20–20 strategy) [1]. EU primary sectors of member states are expected to play a key-role for the success of this attempt. In many cases agricultural activities have focused environmentalists' attention regarding environmental degradation, such as misuse of energy resources, high CO_2 emissions, or overuse of nitrogen fertilizers [2].

The Common Agricultural Policy (CAP), especially after the implementation of the Agenda 2000, has set a series of environmental preconditions which should be satisfied by the farmers, in order to be eligible for receiving both the decoupled and coupled subsidies. The new CAP framework for the 2014–2020

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programming period reinforces the environmental conservation agenda, aiming to increase the efficiency of inputs being used during the agricultural production procedure. Therefore it would be interesting to examine the impact of these policy interventions on both the energy and environmental efficiency of primary sectors of EU member states. This assessment is prepared, by implementing the Data Envelopment Analysis (DEA) methodology for the 2001–2008 time period.

The study is organized as follows: Section 2 provides a comprehensive review of DEA studies related to energy and environmental performance of Decision Making Units (DMUs). Literature review focus both in general DEA studies and in studies of agricultural efficiency. Section 3 presents the proposed methodology and provides an overview of the model variables. Section 4 reports the results of the DEA model and explains in detail the evolution of environmental and energy efficiency of EU's States. Finally, Section 5 summarizes and concludes, including some insights for the further enhancement of environmental friendly agricultural production.

2. Literature review

2.1. General studies

Energy and environmental efficiency are two critical aspects of the global target of sustainable development [3]. Thus, the international literature contains a large number of surveys dealing with these issues [4]. One of the most used methodologies in surveys of energy and environment is DEA [5]. In general, DEA constitutes a method which is based on linear programming and aims at the evaluation of Decision Making Units (DMU). In this manner, DEA may be applied for the efficiency evaluation of any entity that utilizes inputs in order to produce outputs. The method utilizes the theory of production frontiers of Farrell [6] and was first applied by Charnes et al. [7,8].

The greatest advantage of DEA is that it can incorporate multiple inputs and outputs. Furthermore, it is easily applicable as it does not come up with a priori assumptions for the function which links inputs and outputs. In addition, the basic DEA models are amenable to modifications, thus providing sufficient flexibility for adapting the method to different surveys. This strength of DEA is becoming evident from the number of different DEA models that has been used in surveys of energy and environmental evaluation.

Regarding the energy sector efficiency evaluation, it should be noted that papers which are based on this methodology are steadily increasing from 2000 and afterwards. As the first remarkable effort employing DEA in energy efficiency assessment is the paper of Ramanathan [9] who used DEA to assess the differences between the energy efficiency of rail and road transportation nodes. Afterwards, a number of studies relied on the concept of Total Factor Energy Efficiency to evaluate the energy efficiency of Chinese regions [10], Japanese regions [11], APEC Economies [12] and developing countries [13]. In addition, Wei et al. [14] incorporated the Malmquist Index in order to assess the energy efficiency China's iron and steel sectors.

In addition, the literature of DEA studies dealing with environmental aspects of production is surely larger than the relevant of energy studies. Different extensions of the basic DEA models have been employed to estimate the environmental efficiency taking into account the undesirable outputs of the production process. DEA environmental studies could be categorized at the base of two important characteristics. The first one refers to the production reference category [15]. Based on the reference set we can generally classify DEA studies into these employing the strong disposability assumption [16] and to these employing the weak disposability assumption [17,18].

The second characteristic that can be used in order to classify DEA studies is the efficiency measure that these are based on. Two basic categories of studies are formed on the basis of employing radial efficiency measures [19–21] or non-radial efficiency measures [22,23]. In the first type of efficiency measures inputs or outputs are adjusted proportionally while in the second category the adjustments can be non-proportional. In addition, as remarkable extensions of the basic DEA models of environmental efficiency we should consider the Hyperbolic and Directional Distance Functions [18,24–27] and the Slacks Based Measures [28,29].

In addition to the aforementioned studies, a third category which simultaneously measures the efficiency of DMUs, both considering undesirable outputs and energy inputs, is formed. This group of studies could be classified into two subgroups. The first group is formed by studies which calculate a single unified efficiency measure which is labeled as energy or environmental efficiency under the different targets of each survey [30,31,15,32–34]. The second category comprises studies that calculate a composite efficiency index which is the aggregated sum of energy and environmental efficiency indices [35,3,36]. These studies are based on the non-radial DEA models and allow for different values of energy and environmental efficiency. Moreover, the models of these studies provide a better discriminating power than the models that are employed by the surveys of the first category [35].

2.2. Agricultural studies

In the relevant literature of the agricultural sector, efficiency evaluation primarily considers the assessment of the environmental consequences of the production process. The term of sustainable production is in the core of research and special attention is given in the nitrogen efficiency of agricultural production units. More specifically, it was the study of [36] that first decomposed efficiency of agricultural production into three basic elements: technical efficiency, economical efficiency and environmental efficiency. Afterwards a capable number of scholars evaluated the sustainability of agri-production with common reference the estimation of the three basic sub-categories of). More specifically, Lauwers et al. [38] assessed the efficiency of 175 pig fattening farms in Belgium, Asmild and Hougaard [39] evaluated the sustainability of 290 Danish pig farms, Coelli et al. [40] evaluated the efficiency of 183 Belgian pig finishing farms and Thanh Nguyen et al. [41] applied the methodology to 96 rice farms in Gangwon province of South Korea.

Moreover, based on the directional distance function Azad and Ancev [42] used DEA in order to evaluate economic and environmental performance of irrigated agriculture enterprises. The environmental assessment mainly focused on the efficient use of water resources. In addition, Khoshnevisan et al. [34] relied on the basic BCC radial DEA model in order to evaluate the energy and environmental efficiency of open field and greenhouse strawberry production. Finally, Hoang and Rao [43] evaluated the sustainability efficiency of the agriculture sector of 29 OECD countries. Sustainability efficiency is composed by two sub elements. The first refers to the technical efficiency and the second to the energy efficiency of the inputs used in the study.

A thorough study of the aforementioned papers of the agricultural sector reveals two key characteristics that should be highlighted. At the methodological point of view it is evident that sustainability is strongly connected with the efficient use of nitrogen. In most of the studies the energy inputs and the emissions of the production process are not entered into the evaluation process. Thus, the estimated efficiency could not be rewarded as an integrated evaluation of sustainability. One

exception is the paper of Hoang and Rao [43] in which the energy inputs are taken into account through the process of efficiency estimation. Nevertheless, the estimated efficiency in this study is a unified measure in which energy and environmental efficiency are not evaluated in a disaggregated level. On the other hand, analysis is mostly targeting at the micro-level. The only study that provides policy implications at a country level is this of Hoang and Rao [43]. Thus, a lack of studies evaluating agricultural sustainability at regional or national level is observed. As a result there is not a previous effort targeting explicitly at the sustainable efficiency assessment of EU agriculture sector.

3. Model setting and description of the variables

Taking into account the highlighted points in the literature review of agricultural sustainability evaluation studies the contribution of the paper is twofold. On the methodological point of view, the present paper aims to provide an integrated sustainability measure which will depict both environmental and energy efficiency in a disaggregated level. On the other hand, as far as policy making is concerned, the paper constitutes a starting point for the sustainability evaluation of EU's national agricultural sectors. In the next lines the formulation of the model and the variables used in it is explained.

In order to set the model for the energy and environmental efficiency assessment we should split the outputs of production to desirable and undesirable and the inputs to energy and non-energy inputs. When the target is sustainability in production a rational choice of a production unit is to maintain its production results while reducing the undesirable outcomes and using less energy inputs. The common radial efficiency measures of DEA provide the possibility to adjust proportionally the undesirable outputs and energy inputs. However, the proportional adjustments lead to a unified measure of efficiency and thus, these models lack of discriminating power in the assessment of environmental and energy efficiency.

To overcome this limitation it is advisable to adapt a DEA model which will be based on the non-radial efficiency measure. The non-radial measure allows for non-proportional adjustments to inputs and outputs and thus it provides different estimations for energy and environmental efficiency scores. In order to construct the appropriate DEA model for the assessment of EU's national agricultural sectors we follow the customization that firstly implemented by the study of Bian and Yang [35]. To do so we suppose that we have n national agriculture sectors expressed as NAS_j $(j=1,2,\ldots,n)$. The agricultural business of each country use in total m non-energy inputs and k energy inputs to produce d desirable outputs and $s$undesirable outputs. We also assume that $x_{ij}>0$ is the amount of non-energy input i used in total by NAS_j, $e_{cj}>0$ is the amount of energy input c, $y_{dj}>0$ is the amount of desirable output d and $v_{bj}>0$ the amount of non-desirable output b produced by the same NAS. Under the Constant Returns to Scale (CRS) assumption the DEA model of the present study has the following structure:

$$
\begin{aligned}
\mathrm{TE} = \ & \min \frac{1}{2}\left(\frac{1}{k}\sum_{c=1}^{k}\theta_c + \frac{1}{s}\sum_{b=1}^{s}\theta_b\right) \\
\text{s.t.} \ & \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^{x-} = x_{io} \quad i=1,2,\ldots,m \\
& \sum_{j=1}^{n} e_{cj}\lambda_j + s_c^{e-} = \theta_c e_{co} \quad c=1,2,\ldots,k \\
& \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^{y+} = y_{ro} \quad r=1,2,\ldots,d \\
& \sum_{j=1}^{n} v_{bj}\lambda_j = \theta_b v_{bo} \quad b=1,2,\ldots,s \\
& \lambda_j \geq 0 j \ = \ 1,2,\ldots,n \\
& s_i^-, s_c^-, s_r^+ \geq 0
\end{aligned}
\tag{1}
$$

In the above model λ_j are the decision variables which represent the weights NAS j would place on NAS o in constructing its efficient reference set, s_i^-, s_c^- the input slacks and s_r^+ the output slacks. In order to obtain an efficiency score for each NAS we will have to run problem 1 n times. Moreover, θ_c score provides us with a measure of how efficiently each NAS use its resource inputs. Moreover, θ_b illustrates the efficiency of its NAS in producing the same amounts of good outputs keeping the undesirable outputs in the minimum level. Thus, the first part of the equation in the brackets of the objective function $(1/k\sum_{c=1}^{k}\theta_c)$ is a measure of the Total Energy Efficiency (TEnE) of each NAS and the second part $(1/s\sum_{b=1}^{s}\theta_b)$ a measure of the Total Environmental Efficiency (TEnvE) of each NAS. Furthermore, the optimal solution of the objective function of model 1 provides us with a measure of Total Energy and Environmental Efficiency (TEEE) of the NAS inserted to the evaluation. Since, $0<\theta_c, \theta_b \leq 1$ for each c and b it is evident that $0<\mathrm{TEEE}\leq 1$. A NAS would be fully efficient if it is TEEE score equals one and all input and output slacks are zero.

Analysis is targeting at the period 2001–2008. A recursive application of model (1) is conducted at a yearly base. By doing so, we are able to catch time trends in the efficiency of each NAS. The sample is constructed from data of 25 EU member countries.[1] In addition it should be mentioned that a crucial issue in the efficiency assessment of the NAS is the selection of the variables which will adequately represent the production process of the agriculture sector. The conceptual model of primary sector production process and the variables employed, are described in Fig. 1.

4. Results

Fig. 2 presents the evolution of TEEE of EU primary sector member states and its two basic components, TEnE and TEnvE, for the time period 2001–2008. It is worth mentioning that although there are specific environmental preconditions being included in the CAP, the average EU TEnvE in the primary sector declines, especially after the year 2006, when the new decoupled subsidy administration scheme was applied. On the contrary, energy efficiency, after 2007, present significant hints for improvement. The positive change of energy efficiency in 2007–2008 seems to outweigh the decline of environmental efficiency, thus resulting to a positive change of TEEE.

In Fig. 3 the average energy and environmental efficiency of EU member states is being distinguished. The diagram is being divided into four separate regions, according to a line vertical to the x-axis which denotes the average TEnE score (0.78) and a horizontal line representing the average TEnvE (0.732). It is worth mentioning that countries like Germany, Sweden, or Austria, with strong environmental protection standards appear to be less energy and environmentally efficient, compared with countries like Denmark, Belgium, Spain, France, or Ireland. Another quite imortant issue is that Finland, another environmental friendly country, appears to be not efficient enough in its primary sector in both energy and environmental terms. Finally, a series of eastern European countries achieve low efficiency scores, which can be characterized as expectable, due to low technology level being implemented in the primary production process.

[1] Cyprus and Malta are excluded due to lack of reliable data.

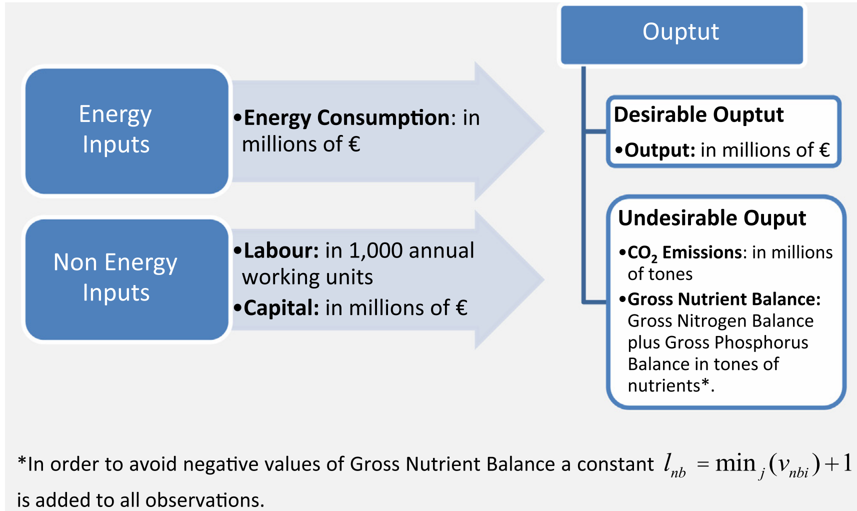

Fig. 1. Primary sector's production process and description of the selected variables.

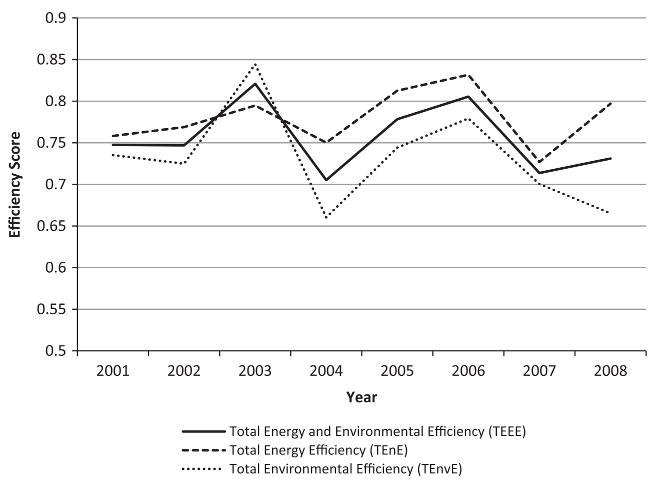

Fig. 2. Evolution of environmental and energy efficiency.

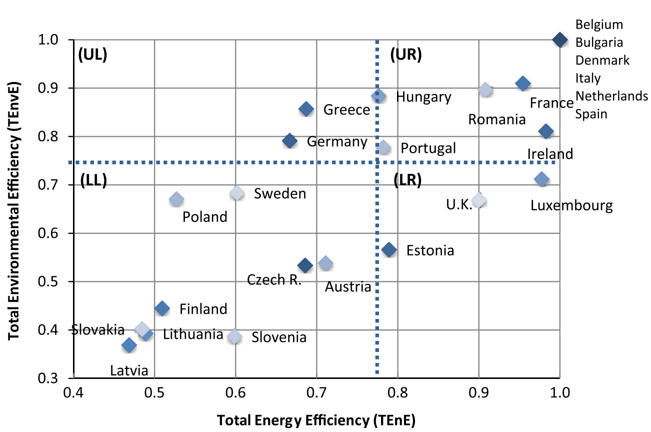

Fig.3. Energy and environmental efficiency matrix.

Finally, Table 1 presents the average efficiency scores in three different ways. In the first column the average efficiency for the period 2001–2008 is presented. The two following columns present are average efficiency scores for two different time periods: the first one with fully coupled subsidies, and the second after the implementation of the decoupled subsidy scheme. Due to lack of data, the number of years for the two sub-periods is not equal. There are, though, significant indications for the majority of member states that the new subsidy management scheme has not motivated further improvement of both energy and environmental efficiency, despite the fact that this was and still is one of the most important goals of the CAP.

Beyond the efficiency leader countries the only ones which have improved their efficiency scores are the UK, Portugal, Germany, Austria, Poland, Lithuania, and Latvia. It is obvious that a series of reasons are behind these deviations of efficiency change among countries, implementing the same agricultural policy for a long period of time. This work cannot provide exact justification on the reasoning of these deviations because of the limited data available. Nevertheless, there are though hints connecting inefficiency with the structure of the primary sector of each EU

Table 1
Efficiency scores per country.

Countries	Average TEEE			Change
	2001–2008	2001–2006	2007–2008	
Denmark	1.000	1.000	1.000	No
Spain	1.000	1.000	1.000	No
Netherlands	1.000	1.000	1.000	No
Italy	1.000	1.000	1.000	No
Belgium	1.000	1.000	1.000	No
Bulgaria	1.000	1.000	1.000	No
France	0.932	0.948	0.884	–
Romania	0.902	1.000	0.609	–
Ireland	0.897	0.948	0.742	–
Luxembourg	0.845	0.873	0.760	–
Hungary	0.830	0.857	0.748	–
United Kingdom	0.784	0.774	0.815	+
Portugal	0.780	0.773	0.801	+
Greece	0.772	0.846	0.550	–
Germany	0.729	0.698	0.820	+
Estonia	0.678	0.681	0.668	–
Sweden	0.651	0.704	0.490	–
Austria	0.624	0.617	0.648	+
Czech Republic	0.610	0.710	0.309	–
Poland	0.599	0.541	0.773	+
Slovenia	0.493	0.533	0.370	–
Finland	0.477	0.504	0.397	–
Slovakia	0.444	0.452	0.419	–
Lithuania	0.439	0.412	0.521	+
Latvia	0.419	0.314	0.733	+
Average	**0.756**	**0.767**	**0.722**	–

+: positive change of efficiency level between two sub-periods. –: negative change of efficiency level between two sub-periods. No: unchanged efficiency level between two sub-periods.

Table 2
Mann–Whitney test results.

Hypothesis	Z Value	Prob. > |z|	Decision
The average TEEE has not been changed significantly after the implementation of the new decoupled subsidy scheme of the CAP	−0.705	0.4801	Not rejected
Average TEEE of old member states does not significantly differ from the TEEE of new member states	−2.26	0.023	Rejected

member. The fact that EU countries which focused on arable crops and intensive animal breeding tend to improve their environmental efficiency after the decoupling of payments, verifies the necessity for these changes, in order for the primary sectors to fully comply with the EU environmental strategy.

All these findings should be reconfirmed after the completion of the period 2007–2013, when all the necessary data will be available. Nevertheless, it is obvious that among EU countries, despite the fact that there is a common agricultural policy being implemented since the establishment of the EU, there are significant variations on very important issues for Europe, like the energy and environmental efficiency. These findings quantify these differences and provide useful information for redesigning the CAP preconditions regarding energy efficiency and environmental protection in the primary sector, to increase cohesion and competitive advantage in a food market where energy and environmental efficiency shape consumer behaviors.

Having in mind Table 1, there are significant hints for considerable changes of energy and environmental efficiency after the implementation of the the new CAP. In oder to verify that, the Mann–Whitney test is being implemented, testing two hypotheses. The fisrt one accepts that the average TEEE has not been changed siginficantly after the implementation of the new decoupled subsidy scheme of the CAP, and the second accepts that there is no significant difference of average TEEE between new and old EU member states. As new members, the countries which accessed EU after the year 2004 are being characterized. Table 2 presents the results of the Mann–Whitney Test.

Based on the available data for the implementation of the new CAP scheme, although that the average TEEE appears to be decreased, this reduction is not statistically signifcant. Thus, the present data does not provide hints for a significant change of environmental and energy efficiency of EU's primary sector. On the contrary, the statistic value $z = -2.26$ with Prob $> |z| = 0.023$ of the second test leads to the rejection of the null hypothesis. This result demonstrates that there is significant difference between the average TEEE of the old and new EU member states, verifying the necessitiy for more intense implementation of environmental friendly policies in the new member states.

5. Conclusions

The present paper is assessing the energy and environmental efficiency of EU member states. The time period being selected covers the two sub-periods of the implementation of different subsidy schemes. The DEA methodology, which was chosen to be used, verified a considerable variation of efficiency scores among countries for both energy and environmental efficiency. Perhaps the most important finding, especially for the old member states, is that although for many years the same CAP is being implemented by every EU country, the variation of efficiency scores is quite large, signifying that other parameters shape the demand for energy and the mix of essential inputs for agricultural production. This variation shapes a quite competitive environment, because efficient and non-efficient countries must promote their agricultural products in a common market with no trade barriers. In the foreseeable future, the environmental friendly production will be one of the most important parameters for shaping a competitive advantage, and there should be strong and measurable evidences for this. The proposed methodology, can be used as a reliable policy assessment tool for such an evaluation.

References

[1] European Commission. COM (2011) 627 final/2; 2011.
[2] Haberl H, Wackernagel M, Krausmann F, Erb K, Monfreda C. Ecological footprints and human appropriation of net primary production: a comparison. Land Use Policy 2004;21:279–88.
[3] Wang K, Wei YM, Zhang X. A comparative analysis of China's regional energy and emission performance: which is the better way to deal with undesirable outputs? Energy Policy 2012;46:574–84.
[4] Song M, An Q, Zhang W, Wang Z, Wu J. Environmental efficiency evaluation based on data envelopment analysis. Rev Renew Sustain Energy Rev 2012;16:4465–9.
[5] Zhou P, Ang BW, Poh KL. A survey of data envelopment analysis in energy and environment studies. **Eur** J Oper Res 2008;189:1–18.
[6] Farrell MJ. The measurement of productive efficiency. J R Stat Soc A 1957;120:253–81.
[7] Charnes A, Cooper WW, Rhodes E. Measuring the efficiency of decision making units. Eur J Oper Res 1978;2:429–44.
[8] Manos B, Psychoudakis A. Investigation and maximisation of the relative efficiency of dairy farms using data envelopment analysis. Q J Int Agric 1997;36(2):188–97.
[9] Ramanathan R. A holistic approach to compare energy efficiencies of different transport modes. Energy Policy 2000;28(11):743–7.
[10] Hu JL, Wang SC. Total-factor energy efficiency of regions in China. Energy Policy 2006;34(17):3206–17.
[11] Honma S, Hu JL. Total-factor energy efficiency of regions in Japan. Energy Policy 2008;36:821–33.
[12] Hu JL, Kao CH. Efficient energy-saving targets for APEC economies. Energy Policy 2007;35(1):373–82.
[13] Zhang XP, Cheng XM, Yuan JH, Gao XJ. Total-factor energy efficiency in developing countries. Energy Policy 2011;39(2):644–50.
[14] Wei YM, Liao H, Fan Y. An empirical analysis of energy efficiency in China's iron and steel sector. Energy 2007;37(4):2262–70.
[15] Zhou P, Ang BW, Poh KL. Measuring environmental performance under different environmental DEA technologies. Energy Econ 2008;30:1–14.
[16] Seiford LM, Zhu J. Modelling undesirable factors in efficiency evaluation. Eur J Oper Res 2002;142:16–20.
[17] Fare R, Grosskopf S, Tyteca D. An activity analysis model of the environmental performance of firms—application to fossil-fuel-fired electric utilities. Ecol Econ 1996;18:161–75.
[18] Chung YH, Fare R, Grosskopf S. Productivity and undesirable outputs: a directional distance function approach. J Environ Manag 1997;51:229–40.
[19] Tyteca D. **L**inear programming models for the measurement of environmental performance of firms—oncepts and empirical results. J Product Anal 1997;8:183–97.
[20] Zaim O. Measuring environmental performance of state manufacturing through changes in pollution intensities: a DEA framework. Ecol Econ 2004;48:37–47.
[21] Yang H, Pollitt M. The necessity of distinguishing weak and strong disposability among undesirable outputs in DEA: environmental performance of Chinese coal-fired power plants. Energy Policy 2010;38(8):4440–4.
[22] Athanassopoulos AD, Lambroukos N, Seiford L. Data envelopment scenario analysis for setting targets to electricity generating plants. Eur J Oper Res 1999;115:413–28.
[23] Sueyoshi T, Goto M. Data envelopment analysis for environmental assessment: comparison between public and private ownership in petroleum industry. Eur J Oper Res 2012;216(3):668–78.
[24] Zofio JL, Prieto AM. Environmental efficiency and regulatory standards: the case of CO2 emissions from OECD industries. Resour Energy Econ 2001;23 (1):63–83.
[25] Boyd GA, Tolley G, Pang J. Plant level productivity, efficiency, and environmental performance of the container glass industry. Environ Resour Econ 2002;23:29–43.
[26] Picazo-Tadeo AJ, Reig-Martınez E, Hernandez-Sancho F. Directional distance functions and environmental regulation. Resour Energy Econ 2005;27:131–42.
[27] Picazo-Tadeo AJ, Beltrán-Esteve M, Gómez-Limón JA. Assessing eco-efficiency with directional distance functions. Eur J Oper Res 2012;220(3):798–809.

[28] Sueyoshi T, Goto M. Slack-adjusted DEA for time series analysis: performance measurement of Japanese electric power generation industry in 1984–1993. Eur J Oper Res 2001;133:232–59.
[29] Agrell PJ, Bogetoft P. Economic and environmental efficiency of district heating plants. Energy Policy 2005;33:1351–62.
[30] Ramanathan R. A multi-factor efficiency perspective to the relationships among world GDP, energy consumption and carbon dioxide emissions. Technol Forecast Soc Change 2006;73:483–94.
[31] Zhou P, Poh KL, Ang BW. A non-radial DEA approach to measuring environmental performance. Eur J Oper Res 2007;178:1–9.
[32] Lozano S, Gutierrez E. Non-parametric frontier approach to modelling the relationships among population, GDP, energy consumption and CO2 emissions. Ecol Econ 2008;66:687–99.
[33] Hernández-Sancho F, Molinos-Senante M, Sala-Garrido R. Energy efficiency in Spanish wastewater treatment plants: a non-radial DEA approach. Sci Total Environ 2011;409(14):2693–9.
[34] Khoshnevisan B, Shariati HM, Rafiee S, Mousazadeh H. Comparison of energy consumption and GHG emissions of open field and greenhouse strawberry production. Renew Sustain Energy Rev 2014;29:316–24.
[35] Bian YW, Yang F. Resource and environment efficiency analysis of provinces in China: a DEA approach based on Shannon's entropy. Energy Policy 2010;38:1909–17.
[36] Wang K, Yu S, Zhang W. China's regional energy and environmental efficiency: a DEA window analysis based dynamic evaluation. Math Comput Model 2013;58:1117–27.
[38] Lauwers L, Van Huylenbroeck G, Materials balance based modelling of environmental efficiency. In: Proceedings of the 25th international conference of agricultural economist, Durban, South Africa; (2003).
[39] Asmild M, Hougaard JL. Economic versus environmental improvement potentials of Danish pig farms. Agric Econ 2006;35(2):171–81.
[40] Coelli T, Lauwers L, Van Huylenbroeck G. Environmental efficiency measurement and the materials balance condition. J Prod Anal 2007;28(1-2):3–12.
[41] Thanh Nguyen T, Hoang VN, Seo B. Cost and environmental efficiency of rice farms in South Korea. Agric Econ 2012;43(4):369–78.
[42] Azad MA, Ancev T. Using ecological indices to measure economic and environmental performance of irrigated agriculture. Ecol Econ 2010;69(8):1731–9.
[43] Hoang VN, Rao DS. Measuring and decomposing sustainable efficiency in agricultural production: a cumulative energy balance approach. Ecol Econ 2010;69(9):1765–76.